flow sheet from Aso caldera, southwestern Japan, *Contrib. Mineral. Petrol., 16,* 300–327, 1967.
Macdonald, G. A., A contribution to the petrology of Tutuila, American Samoa, *Geol. Rundsch., 57,* 821–837, 1968.
Malahoff, A., Origin of magnetic anomalies over the central volcanic region, in *The Crust and Upper Mantle of the Pacific Area, Geophys. Monogr. 12,* pp. 218–240, AGU, Washington, D.C., 1968.
McBirney, A. R., and H. Williams, Geology and petrology of the Galapagos Islands, *Geol. Soc. Amer. Mem. 118,* 1–198, 1969.
Melson, W. G., E. Jarosewich, and C. A. Lundquist, Volcanic eruption at Metis Shoal, Tonga, 1967–1968: Description and petrology, *Smithson. Contrib. Earth Sci., 4,* 1–18, 1970.
Moore, J. G., and W. G. Melson, Nuees ardentes of the 1968 eruption of Mayon volcano, Philippines, *Bull. Volcanol., 33,* 600–620, 1969.
Moxham, R. M., Changes in surface temperature at Taal volcano, Philippines, 1965–1966, *Bull. Volcanol., 31,* 215–234, 1967.
Simkin, T., and K. A. Howard, Caldera collapse in the Galapagos Islands, 1968, *Science, 169,* 429–437, 1970.
Stice, G. D., and F. W. McCoy, Jr., The geology of the Manu's Islands, Samoa, *Pac. Sci., 22,* 427–457, 1968.
Ward, P. L., G. Palmason, and C. Drake, Microearthquake survey and the mid-Atlantic ridge in Iceland, *J. Geophys. Res., 74,* 665–684, 1969.

Submarine Eruptions

Bonatti, Enrico, Mechanisms of deep-sea volcanism in the South Pacific, in *Researches in Geochemistry, vol. 2,* edited by P. H. Abelson, pp. 453–491, John Wiley, New York, 1967.
Moore, J. G., Pillow lava in a historic lava flow from Hualalai volcano, Hawaii, *J. Geol., 78,* 239–243, 1970.
Moore, J. G., and R. S. Fiske, Volcanic substructure, inferred from dredge samples and ocean-bottom photographs, Hawaii, *Bull. Geol. Soc. Amer., 80,* 1191–1202, 1969.
Norris, R. A., and R. N. Johnson, Submarine volcanic eruptions recently located in the Pacific by Sofar hydrophones, *J. Geophys. Res., 74,* 650–664, 1969.
Shepherd, J. B., and G. R. Robson, The source of the *T* phase recorded in the eastern Caribbean on October 24, 1965, *Bull. Seismol. Soc. Amer., 57,* 227–234, 1967.
Sykes, L. R., Earthquake swarms and sea-floor spreadings, *J. Geophys. Res., 75,* 6598–6611, 1970.

General

Decker, R. W., A seismic event counter for active volcanoes, *Bull. Seismol. Soc. Amer., 58,* 1353–1358, 1968.
Eaton, J. P., A computer program for determining hypocenters of local earthquakes in an earth consisting of uniform flat layers over a half-space, *U.S. Geol. Surv. Open File Rep.,* 1969.
Eggers, A. A., and R. W. Decker, Frequency of historic volcanic eruptions (abstract), *EOS, Trans. AGU, 50,* 343, 1969.
Friedman, J. D., and R. S. Williams, Jr., Infrared sensing of active geologic processes, in *Proceedings of Fifth Symposium on Remote Sensing of Environment,* Ann Arbor, Mich., Run Labs, pp. 787–815, 1968.
McBirney, A. R., Some current aspects of volcanology, *Earth Sci. Rev.,* in press, 1971.
Melson, W. G., T. Simkin, R. S. Fiske, J. G. Moore, and R. W. Decker, Major volcanic eruptions of 1968: Preliminary contributions to petrology and volcanology (abstract), *EOS, Trans. AGU, 50,* 344, 1969.
Moore, J. G., Base surge in recent volcanic eruptions, *Bull. Volcanol., 30,* 337–363, 1967.
Moxham, R. M., Thermal surveillance of volcanoes, in *Prediction of Volcanic Eruptions,* edited by T. Minikami, Paris, in press, 1971.
Slaughter, M., and M. Hamil, Model for deposition of volcanic ash and resulting bentonite, *Bull. Geol. Soc. Amer., 81,* 961–968, 1970.
Smithsonian Institution Center for Short-Lived Phenomena: Annual Progress Report, 1968.
Smithsonian Institution Center for Short-Lived Phenomena: Annual Progress Report, 1969.
Tryggvason, E., Surface deformation on and near three volcanoes in Iceland (abstract), *EOS, Trans. AGU, 51,* 441, 1970.

Petrologic Aspects of Plate Tectonics

Peter J. Wyllie

The concept of plate tectonics has developed during the past four years from the hypotheses of continental drift and sea-floor spreading, supported by a variety of evidence from paleomagnetism, geochronology, and marine geology and geophysics. A series of four contiguous papers in the March 1968 issue of the *Journal of Geophysical Research* correlated on a global scale the linear magnetic anomalies, which are parallel to and bilaterally symmetrical about the oceanic ridge system, with the polarity reversals of the earth's magnetic field imprinted on new oceanic crust as it was generated at the oceanic ridge crests [*Pitman et al.,* 1968; *Dickson et al.,* 1968; *Le Pichon and Heirtzler,* 1968; *Heirtzler et al.,* 1968]. In 1967 and 1968, four major papers introduced plate tectonics: the earth's surface is considered to be made up of a few rigid crustal plates or blocks in motion relative to each other [*McKenzie and Parker,* 1967; *Morgan,* 1968; *Le Pichon,* 1968; *Isacks et al.,* 1968].

Wilson's [1965] concept of transform faults was extended to a spherical surface by McKenzie and Parker and by Morgan. McKenzie and Parker outlined the elements of plate tectonics (paving-stone theory). Morgan formalized the concept, dividing the earth's surface into about twenty rigid plates. Le Pichon presented a global model with only six major plates. Plate boundaries are of three types: extensive oceanic ridges where new crust is generated, compressive oceanic trenches where crust is destroyed, and transform faults where crustal surface is neither created nor destroyed. Earthquake belts follow the boundaries to the series of essentially aseismic plates. There is now evidence for smaller plates moving relative to the larger plates around them, as in the Caribbean region [*Molnar and Sykes,* 1969]. In the fourth paper, Isacks, Oliver, and Sykes dealt specifically with the strong support given by seismological observations and interpretations to the concept of 'the new global tectonics.' Results obtained in Joides leg 3 across the mid-Atlantic ridge, reported by Maxwell and seven co-authors [*Maxwell et al.,* 1970], provide striking evidence in support of the model.

Peter J. Wyllie is with the Department of Geophysical Sciences, University of Chicago, Chicago, Illinois 60636.

I started to survey the literature journal by journal for the past four years, but since the plate-tectonics revolution was announced [*Wilson*, 1968; *Beloussov*, 1968] so many papers include reference to plate tectonics that I abandoned this procedure. This report relies heavily on recent review papers that provide entrance into the earlier literature of this four-year period.

The concept of plate tectonics is forcing geologists to reconsider everything that they thought they knew about geology. A Penrose Conference of the Geological Society of America convened in December 1969 to discuss 'The Meaning of the New Global Tectonics for Magmatism, Sedimentation, and Metamorphism in Orogenic Belts.' *Dickinson* [1970] published a report of the meeting. The topics that received particular attention included (1) andesite chains, (2) batholith belts, (3) ophiolite complexes, (4) blueschist metamorphism, (5) relationship of continental structures to subduction zones beneath island arcs and continental margins, and (6) the meaning of geosynclinal theory in the new conceptual framework. A review paper by *Dewey and Bird* [1970] on 'Mountain Belts and the New Global Tectonics' outlined in some detail many of the geological and petrological aspects of plate tectonics, with particular attention to the compressive plate boundaries. The topics listed above, and other petrological aspects of plate tectonics, can be considered with respect to (1) oceanic ridges and associated transform fracture zones, (2) island arcs and continental margins associated with oceanic trenches, and (3) the rigid plates.

The temperature distribution at depth is one fundamental control on petrological processes. Estimates of temperature vary greatly, depending on the assumptions regarding the significance for heat transfer of conduction, radiation, and convection. At 500-km depth there is a difference of about 1000°C between estimated geotherms for a conduction model [*Lubimova*, 1967] and for a convection model [*Tozer*, 1967]. Other estimates involving conduction and radiation lie between these limits.

According to plate tectonics, temperatures beneath oceanic ridges are high because of rising mantle material. *Oxburgh and Turcotte* [1968] presented a steady-state distribution of isotherms beneath an oceanic ridge, computed on the basis of boundary-layer theory, and assuming constant viscosity independent of temperature (see also *Turcotte and Oxburgh*, 1969). An alternative to this model of broad upwelling is the injection of dykes from the low-velocity zone into a narrow axial zone [*McKenzie*, 1967; *Sleep*, 1969].

A sinking slab of lithosphere in a subduction zone extending downward from an oceanic trench lowers mantle temperatures, but heat may be generated around the margins of the cold slab as it moves through the mantle. The distribution of geotherms beneath island arcs and continental margins has been calculated or illustrated by *McKenzie* [1969], *McBirney* [1969], *Minear and Toksöz* [1970], and *Oxburgh and Turcotte* [1970].

Deformation experiments on peridotite and dunite suggest that flow in the upper mantle may be governed by a nonlinear creep law [*Carter and Ave Lallemant*, 1970] and the fabric produced experimentally by syntectonic recrystallization of olivine is similar to fabrics in some ultramafic nodules derived from the mantle [*Avé Lallemant and Carter*, 1970]. This has implications for seismic anisotropy of the upper mantle.

Much has been learned about the structure and petrology of the oceanic ridges in recent years. According to *van Andel* [1968], an original terrane of fissure-erupted basalts is subsequently deformed by faulting, rifting, and uplift. *Melson et al.*, [1968] referred to three types of topography: linear topography, cross-fracture zones, and regions with abundant volcanoes. Fissure eruptions dominate, with abyssal tholeiites or their metamorphosed equivalents commonly dredged from the ridge crests [*Melson and van Andel*, [1966]. Peridotites, serpentinites, and gabbros occur in the fracture zones, and alkali olivine basalts are dredged from the upper flanks of volcanoes [*van Andel et al.*, 1967; *Melson et al.*, 1968]. There appear to be correlations between petrology and relief. *Menard* [1967] suggested that the volume of lava discharged at the ridge into layer 2, per unit time per unit length, is relatively constant regardless of the spreading rate.

The chemistry and mineralogy of basalts dredged from the ridges has been described by *Aumento* [1967, 1968], *Melson et al.*, [1968], *McBirney and Gass* [1967], *Miyashiro et al.* [1969*a*, 1970*a*, *b*], *Gast* [1968], *Frey et al.* [1968] and *Kay et al.* [1970]. Differentiation products have been described by *Miyashiro et al.* [1970*b*] and *Aumento* [1969]. *Aumento* [1969] described in situ diorites associated with basalts and serpentinites on fault scarps. *Aumento* [1967, 1968] and *McBirney and Gass* [1967] discussed variations in basalt composition with distance from ridge crest and depth of eruption, a topic pursued in many subsequent papers. *Melson and Thompson* [1970] described gabbroic cumulates dredged from the Romanche fracture zone, and cited this as evidence for the existence of layered basic complexes in the oceanic crust. *Engel and Fisher* [1969] reported anorthosite from the mid-Indian Ocean ridge.

Peridotites, serpentinites, and other plutonic rocks appear to floor the cross-fracture zones [*van Andel et al.*, 1967]. The amphibole-bearing mylonite peridotites and associated alkalic ultrabasic rocks of St. Paul's Rocks above the mid-Atlantic ridge were described by *Melson et al.* [1967] and *Frey* [1970]. *Engel and Fisher* [1969] described lherzolites from cross fractures in the mid-Indian Ocean ridge and noted their chemical similarity to the St. Paul's Rocks peridotites. *Miyashiro et al.* [1969*b*] reported a detailed study of serpentinites from the mid-Atlantic ridge and concluded that these, too, were chemically similar to the St. Paul's Rocks. *Vine and Hess* [1970] reviewed the distribution of peridoties and serpentinites in the oceans.

Melson and van Andel [1966] described greenstones from the ridge crest that had apparently been metamorphosed beneath an overburden of about 2 km at a temperature of about 300°C. Metamorphosed basalts and gabbros have since been reported by many investigators, including *Melson et al.* [1968], *Miyashiro et al.*

[1969*a*, 1970*a*]. Hot, possibly saline solutions may be involved in the metamorphism. The metamorphosed rocks are exposed in fault scarps. *Christensen* [1970] concluded that seismic velocities in the lower oceanic crust were consistent with the presence of abundant greenschists. Grossular garnet is a minor component in some dredged lherzolites [*Engel and Fisher,* 1969] and andradite garnets have been found in serpentinized peridotite [*Switzer et al.,* 1970].

The magnetic properties of the ridge and its flanks are controlled by the petrology. *Phillips et al.* [1969] reported a narrow fracture zone near 43°N across the mid-Atlantic ridge, which appeared to separate a northern region floored by serpentinized peridotites from a southern region floored by basalts. The northern region had no central rift, no obvious magnetic symmetry elements, and high heat flow. The southern region had a well-developed rift and symmetrical magnetic anomaly pattern, both terminating abruptly at the fracture zone, and low heat flow. The state of magnetization of submarine basalts and the causes of magnetic anomalies in oceanic crustal material are not adequately known [*Watkins and Richardson,* 1968]. Magnetic studies of basalts dredged from the ocean have been reported by *Ozima et al.* [1968] and *de Boer et al.* [1969]. *Miyashiro et al.* [1970*a*] suggested that the magnetic anomalies were caused by a superficial layer of strongly magnetized basalt overlying rocks that had lost their magnetic properties through metamorphism.

Models for the generation of new crust at the oceanic ridges involve the petrology of the basalts and peridotites, and their metamorphosed equivalents. *Aumento* [1967] proposed a model relating a variety of magma types to structures and dynamic processes associated with the ridges, and *Gast* [1968] proposed a similar, more quantitative model based on the convection scheme of *Oxburgh and Turcotte* [1968]. *Kay et al.* [1970] extended these discussions further. Alternative interpretations of the petrology giving different models for sea-floor spreading were considered by *Miyashiro et al.* [1970*a*]. *Vogt et al.* [1969] reviewed petrological models. *Melson and Thompson* [1970] reviewed four processes involved in the formation of oceanic crust, including the development of layered basic complexes. *Thayer* [1969] suggested that the peridotite-gabbro complexes of orogenic belts may provide the key to interpretation of the petrology of mid-oceanic ridges. *Dewey and Bird* [1970] suggested that the ophiolite complexes of orogenic belts represent upper mantle and oceanic crust generated at oceanic ridge systems, translated laterally by sea-floor spreading, and incorporated tectonically at low temperatures into orogenic belts.

Murray [1970] pointed out that the alkalic volcanic activity associated with African rift valleys since pre-Cenozoic time opposes the concept that they represent an embryonic stage of the spreading process. The volcanism differs significantly, in composition and volume, from that at oceanic ridges.

Petrological aspects of plate tectonics at compressive plate junctures, island arcs, and active continental margins, include interpretation of ophiolites and other ultramafic rocks of the orogenic belts, the conditions for metamorphism, and the possible involvement of oceanic sediments in subduction zones, the origin of andesites and high-alumina basalts, and the origin of batholiths.

Recent opinions about the origin of ophiolites and other orogenic ultramafic rocks have been reviewed by *Wyllie* [1970]. *Thayer* [1969] discussed their relationship to oceanic ridges and the oceanic crust. *Dewey and Bird* [1970] emphasized the fundamental importance of the ophiolite suite in evaluating the stages of development of mountain belts. *Hamilton* [1969], *Gresens* [1970], and *Moiseyev* [1970] discussed the origin of serpentinites in connection with a former subduction zone dipping beneath California.

Dewey and Bird [1970] and *Oxburgh and Turcotte* [1970] illustrated schematically how blueschist metamorphism could be caused by rapid plate consumption. It is generally assumed that some sediment is carried down into the mantle with the sinking oceanic plate, and that some of it is mechanically plastered by folding onto the continental margin or island arc. There has been considerable discussion about the behavior of sediments in oceanic trenches, because many of them show only tensional features, whereas compressional deformation is expected from plate tectonic theory. The problem is complex, and it has been reviewed recently by *Scholl et al.* [1970]. The blueschists of the California Coast Ranges have been interpreted in terms of underflow of the Pacific mantle plate along a Benioff zone during the Mesozoic by *Hamilton* [1969] and *Ernst* [1970]; see also *Page* [1970]. *Gresens* [1970] accepted underthrusting for this region, but he interpreted the blueschists as metastable rocks formed by fluids generated during serpentinization.

The origin of andesites and other volcanic rocks of the calc-alkalic suite by partial fusion of sediments and crust of a downgoing slab of oceanic lithosphere has been reviewed in general terms by *Dewey and Bird* [1970] and *Oxburgh and Turcotte* [1970]. It has been established by *Dickinson and Hatherton* [1967], *Dickinson* [1968], and *Hatherton and Dickinson* [1969] that the ratio K_2O/SiO_2 in andesites from circum-Pacific and other island arcs increases in transverse direction across the arc from the ocean. The K_2O content of the lavas is closely correlated with the depth from the volcanoes to the inclined seismic zones beneath the arcs. The authors place the source of the andesite magmas in the sinking slab, at depths of 100 to 300 km. Similar chemical variations appear to exist in batholiths; they have been established for the Sierra Nevada batholith [*Bateman and Dodge,* 1970]. *Raleigh and Lee* [1969] illustrated descending oceanic lithosphere, with successive dehydration reactions occurring as oceanic crust was converted from serpentinite and basalt to peridotite and blueschist, and the blueschist was converted to amphibolite and eclogite; andesite formed by partial fusion of the eclogite at depth. Dehydration of the lithosphere slab, followed by upward migration of water into the warmer overlying mantle, could produce partial fusion as proposed by *McBirney* [1969] and *Hamilton* [1969]. This process has been postulated as a source of intermediate and acid magmas for andesites and for batholiths. Metamorphism associated with this part of the island arc is presumably of the moderate-pressure/high-temperature type, in contrast with the high-pressure/low-temperature type producing blueschists in the trench region.

The application of plate tectonic theory to the Mesozoic evolution of western North America by *Hamilton* [1969], by *Gilluly et al.* [1970], and by *Ernst* [1970] introduced a number of petrological interpretations. *Bird and Dewey* [1970] applied plate tectonic theory, with petrological interpretations, to the evolution of the Appalachian Caledonian orogenic belt. *Ziegler* [1970] unraveled the geosynclinal development of the British Isles during the Silurian, in terms of plate tectonic theory. He concluded that the Atlantic Ocean was open during the Lower Paleozoic, closed, and reopened in the Mesozoic along a slightly different line. *Hamilton* [1970] reviewed the geology and the igneous and metamorphic petrology of the Uralides between the Russian and Siberian platforms, and deduced a history of continental margins before and during the collisons of these two plates, assumed originally to have been separated.

The eruption of lava above a rigid plate, far removed from plate boundaries, does not fit neatly into plate tectonic schemes. There is evidence that volcanoes formed in plates also drift. *Menard* [1969] reviewed the growth of drifting volcanoes.

Some petrological observations appear only on predrift continental reconstructions [*Bullard et al.*, 1965; *Dietz and Holden*, 1970]. *Herz* [1969] noted continuity of ancient anorthosite belts. *Hurley* [1970] noted that the distribution of age provinces in Laurasia is vaguely concentric, with increasingly younger mobile belts disposed peripherally around an inner ring of ancient cratons.

Plate tectonics has enjoyed such phenomenal success as a working hypothesis that it is fast becoming a ruling theory. The model provides a framework for the interpretation of petrology in various environments. On the other hand, petrology provides information that can be used to support the models. It is obviously necessary to guard against circular arguments. The international Upper Mantle Project terminated in 1970. It is replaced by a Geodynamics Project, and this international, interdisciplinary program will continue to make petrology, geochemistry, and geophysics mutually dependent on each other.

REFERENCES

Aumento, F., Magmatic evolution on the mid-Atlantic ridge, *Earth Planet. Sci. Lett.*, *2*, 225–230, 1967.

Aumento, F., Mid-Atlantic ridge near 45°N, 2, Basalts from the area of Confederation peak, *Can. J. Earth Sci.*, *5*, 1–21, 1968.

Aumento, F., Diorites from the mid-Atlantic ridge at 45°N, *Science*, *165*, 1112–1113, 1969.

Avé Lallemant, H. G., and N. L. Carter, Syntectonic recrystallization of olivine and modes of flow in the upper mantle, *Bull. Geol. Soc. Amer.*, *81*, 2203–2220, 1970.

Bateman, P. C., and F. C. W. Dodge, Variations of major chemical constituents across the central Sierra Nevada batholith, *Bull. Geol. Soc. Amer.*, *81*, 409–420, 1970.

Beloussov, V. V., An open letter to J. Tuzo Wilson, *Geotimes*, *13*(10), 17–19, 1968.

Bird, J. M., and J. F. Dewey, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen, *Bull. Geol. Soc. Amer.*, *81*, 1031–1060, 1970.

Bullard, E. C., J. E. Everett, and A. G. Smith, The fit of the continents around the Atlantic, *Phil. Trans. Roy. Soc. London, A*, *258*, 41–51, 1965.

Carter, N. L., and H. G. Avé Lallemant, High-temperature flow of dunite and peridotite, *Bull. Geol. Soc. Amer.*, *81*, 2181–2202, 1970.

Christensen, N. I., Possible greenschist facies metamorphism of the oceanic crust, *Bull. Geol. Soc. Amer.*, *81*, 905–908, 1970.

de Boer, J., J. G. Schilling, and D. C. Krause, Magnetic polarity of pillow basalts from Reykjanes ridge, *Science*, *166*, 996–998, 1969.

Dewey, J. F., and J. M. Bird, Mountain belts and the new global tectonics, *J. Geophys. Res.*, *75*, 2625–2647, 1970.

Dickinson, W. R., Circum-Pacific andesite types, *J. Geophys. Res.*, *73*, 2261–2269, 1968.

Dickinson, W. R., Evolution of calc-alkaline rocks in the geosynclinal system of California and Oregon, in *Proceedings of the Andesite Conference*, edited by A. R. McBirney, *Oregon Dep. Geol. Mineral Ind., Bull. 65*, 1969.

Dickinson, W. R., Global tectonics, *Science*, *168*, 1250–1259, 1970.

Dickinson, W. R., and T. Hatherton, Andesitic volcanism and seismicity around the Pacific, *Science*, *157*, 801–803, 1967.

Dickson, G. O., W. C. Pitman, and J. R. Heirtzler, Magnetic anomalies in the South Atlantic and ocean-floor spreading, *J. Geophys. Res.*, *73*, 2087–2100, 1968.

Dietz, R. S., and J. C. Holden, Reconstruction of Pangaea: Breakup and dispersion of continents, Permian to present, *J. Geophys. Res.*, *75*, 4939–4956, 1970.

Engel, C. G., and R. L. Fisher, Lherzolite, anorthosite, gabbro, and basalt dredged from the mid-Indian ocean ridge, *Science*, *166*, 1136–1141, 1969.

Ernst, W. G., Tectonic contract between the Franciscan melange and the Great Valley sequence–Crustal expression of a late Mesozoic Benioff zone, *J. Geophys. Res.*, *75*, 886–901, 1970.

Frey, F. A., Rare earths and potassium abundances in St. Paul's Rocks, *Earth Planet. Sci. Lett.*, *7*, 351–360, 1970.

Frey, F. A., M. A. Haskin, J. A. Poetz, and L. A. Haskin, Rare earth abundances in some basic rocks, *J. Geophys. Res.*, *73*, 6085–6098, 1968.

Gast, P. W., Trace-element fractionation and the origin of tholeiitic and alkaline magma types, *Geochim. Cosmochim. Acta*, *32*, 1057–1068, 1968.

Gilluly, J., J. C. Reed, and W. M. Cady, Sedimentary volumes and their significance, *Bull. Geol. Soc. Amer.*, *81*, 353–376, 1970.

Gresens, R. L., Serpentinites, blueschists, and tectonic continental margins, *Bull. Geol. Soc. Amer.*, *81*, 307–310, 1970.

Hamilton, W., Mesozoic California and the underflows of Pacific mantle, *Bull. Geol. Soc. Amer.*, *80*, 2409–2430, 1969.

Hamilton, W., The Uralides and the motion of the Russian and Siberian platforms, *Bull. Geol. Soc. Amer.*, *81*, 2553–2576, 1970.

Hatherton, T., and W. R. Dickinson, The relationship between andesitic volcanism and seismicity in Indonesia, the Lesser Antilles, and other island arcs, *J. Geophys. Res.*, *74*, 5301–5310, 1969.

Heirtzler, J. R., G. O. Dickson, E. M. Herron, W. C. Pitman, and X. Le Pichon, Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents, *J. Geophys. Res.*, *73*, 2119–2136, 1968.

Herz, N., Anorthosite belts, continental drift, and the anorthosite event, *Science*, *164*, 944–947, 1969.

Hurley, P. M., Distribution of age provinces in Laurasia, *Earth Planet. Sci. Lett.*, *8*, 189–196, 1970.

Isacks, B., J. Oliver, and L. R. Sykes, Reply to comments on 'Seismology and the new global tectonics,' *J. Geophys. Res.*, *74*, 2789–2790, 1969.

Kay, R., N. J. Hubbard, and P. W. Gast, Chemical characteristics and origin of oceanic ridge volcanic rocks, *J. Geophys. Res., 75,* 1585–1613, 1970.

Le Pichon, X., Sea-floor spreading and continental drift, *J. Geophys. Res., 73,* 3661–3697, 1968.

Le Pichon, X., and J. R. Heirtzler, Magnetic anomalies in the Indian Ocean and sea-floor spreading, *J. Geophys. Res., 73,* 2101–2117, 1968.

Lubimova, E. A., Theory of thermal state of the earth's mantle, in *The Earth's Mantle,* edited by T. F. Gaskell, 509 pp., Academic, New York, 1967.

McBirney, A. R., Compositional variations in Cenozoic calc-alkaline suites of Central America, *Oregon Dep. Geol. Mineral Ind., Bull. 65,* 185–189, 1969.

McBirney, A. R., and I. G. Gass, Relations of oceanic volcanic rocks to mid-ocean rises and heat flow, *Earth Planet. Sci. Lett., 2,* 265–276, 1967.

McKenzie, D. P., Some remarks on heat flow and gravity anomalies, *J. Geophys. Res., 72,* 6261–6273, 1967.

McKenzie, D. P., Speculations on the consequences and causes of plate motions, *Geophys. J., 18,* 1–32, 1969.

McKenzie, D. P., and R. L. Parker, The North Pacific: An example of tectonics on a sphere, *Nature, 216,* 1276–1280, 1967.

Maxwell, A. E., R. P. Von Herzen, K. J. Hsu, J. E. Andrews, T. Saito, S. F. Percival, E. D. Milow, and R. E. Boyce, Deep sea drilling in the South Atlantic, *Science, 168,* 1047–1059, 1970.

Melson, W. G., and G. Thompson, Layered basic complex in oceanic crust, Romanche fracture, equatorial Atlantic Ocean, *Science, 168,* 817–820, 1970.

Melson, W. G., and Tj. H. van Andel, Metamorphism in the mid-Atlantic ridge, 22°N latitude, *Mar. Geol., 4,* 165–186, 1966.

Melson, W. G., E. Jarosewich, V. T. Bowen, and G. Thompson, St. Peter and St. Paul Rocks: A high-temperature, mantle-derived intrusion, *Science, 155,* 1532–1535, 1967.

Melson, W. G., G. Thompson, and Tj. H. van Andel, Volcanism and metamorphism in the mid-Atlantic ridge, 22°N latitude, *J. Geophys. Res., 73,* 5925–5941, 1968.

Menard, H. W., Sea-floor spreading, topography, and the second layer, *Science, 157,* 923–924, 1967.

Menard, H. W., Growth of drifting volcanoes, *J. Geophys. Res., 74,* 4827–4837, 1969.

Minear, J. W., and M. N. Toksöz, Thermal regime of a downgoing slab and new global tectonics, *J. Geophys. Res., 75,* 1397–1419, 1970.

Miyashiro, A., F. Shido, and M. Ewing, Diversity and origin of abyssal tholeiite from the mid-Atlantic ridge near 24° and 30° north latitude, *Contrib. Mineral. Petrol., 23,* 38–52, 1969*a*.

Miyashiro, A., F. Shido, and M. Ewing, Composition and origin of serpentinites from the mid-Atlantic ridge near 24° and 30° north latitude, *Contrib. Mineral. Petrol., 23,* 117–127, 1969*b*.

Miyashiro, A., F. Shido, and M. Ewing, Petrologic models for the mid-Atlantic ridge, *Deep-Sea Res., 17,* 109–123, 1970*a*.

Miyashiro, A., F. Shido, and M. Ewing, Crystallization and differentiation in abyssal tholeiites and gabbros from mid-oceanic ridges, *Earth Planet. Sci. Lett., 7,* 361–365, 1970*b*.

Moiseyev, A. N., Late serpentinite movements in the California Coast Ranges: New evidence and its implications, *Bull. Geol. Soc. Amer., 81,* 1721–1732, 1970.

Molnar, P., and L. R. Sykes, Tectonics of the Caribbean and Middle America regions from focal mechanisms and seismicity, *Bull. Geol. Soc. Amer., 80,* 1639–1684, 1969.

Morgan, W. J., Rises, trenches, great faults, and crustal blocks, *J. Geophys. Res., 73,* 1959–1982, 1968.

Murray, G. C., Magma genesis and heat flow: Differences between mid-oceanic ridges and African rift valleys, *Earth Planet. Sci. Lett., 9,* 34–38, 1970.

Oxburgh, E. R., and D. L. Turcotte, Mid-ocean ridges and geotherm distribution during mantle convection, *J. Geophys. Res., 73,* 2643–2661, 1968.

Oxburgh, E. R., and D. L. Turcotte, Thermal structure of island arcs, *Bull. Geol. Soc. Amer., 81,* 1665–1688, 1970.

Ozima, M., M. Ozima, and I. Kaneoka, Potassium-argon ages and magnetic properties of some dredged submarine basalts and their geophysical implications, *J. Geophys. Res., 73,* 711–723, 1968.

Page, B. M., Sur-Nacimiento fault zone of California: Continental margin tectonics, *Bull. Geol. Soc. Amer., 81,* 667–690, 1970.

Phillips, J. D., G. Thompson, R. P. Von Herzen, and V. T. Bowen, Mid-Atlantic ridge near 43°N latitude, *J. Geophys. Res., 74,* 3069–3081, 1969.

Pitman, W. C., E. M. Herron, and J. R. Heirtzler, Magnetic anomalies and sea floor spreading, *J. Geophys. Res., 73,* 2069–2085, 1968.

Raleigh, C. B., and W. H. K. Lee, Sea-floor spreading and island-arc tectonics, in *Proceedings of the Andesite Conference,* edited by A. R. McBirney, *Oregon Dep. Geol. Mineral Ind. Bull. 65,* 1969.

Scholl, D. W., M. N. Christensen, R. Von Huene, and M. S. Marlow, Peru-Chile trench sediments and sea-floor spreading, *Bull. Geol. Soc. Amer., 81,* 1339–1360, 1970.

Sleep, N. H., Sensitivity of heat flow and gravity to the mechanism of sea-floor spreading, *J. Geophys. Res., 74,* 542–549, 1969.

Switzer, G., W. G. Melson, and G. Thompson, Garnet from the mid-Atlantic ridge near 43°N latitude, *Bull. Geol. Soc. Amer., 81,* 895–898, 1970.

Thayer, T. P., Peridotite-gabbro complexes as keys to petrology of mid-oceanic ridges, *Bull. Geol. Soc. Amer., 80,* 1515–1522, 1969.

Tozer, D. C., Towards a theory of thermal convection in the mantle, in *The Earth's Mantle,* edited by T. F. Gaskell, 509 pp., Academic, New York, 1967.

Turcotte, D. L., and E. R. Oxburgh, Convection in a mantle with variable physical properties, *J. Geophys. Res., 74,* 1458–1474, 1969.

van Andel, Tj. H., The structure and development of rifted mid-ocean rises, *J. Mar. Res., 26,* 144–161, 1968.

van Andel, Tj. H., J. B. Corliss, and V. T. Bowen, The intersection between the mid-Atlantic ridge and the Vema fracture zone in the North Atlantic, *J. Mar. Res., 25,* 343–351, 1967.

Vine, F. J., and H. H. Hess, Sea-floor spreading, in *The Sea,* vol. 4, edited by A. E. Maxwell, E. C. Bullard, E. Goldberg, and J. L. Worzel, Interscience, New York, 1970.

Vogt, P. R., E. D. Schneider, and G. L. Johnson, The crust and upper mantle beneath the sea, in *The Earth's Crust and Upper Mantle, Geophys. Monogr. 13,* edited by P. J. Hart, 735 pp., AGU, Washington, D.C., 1969.

Watkins, N. D., and A. Richardson, Comments on the relationship between magnetic anomalies, crustal spreading and continental drift, *Earth Planet. Sci. Lett., 4,* 257–264, 1968.

Wilson, J. T., Transform faults oceanic ridges, and magnetic anomalies southwest of Vancouver Island, *Science, 150,* 482–485, 1965.

Wilson, J. T., A revolution in earth science, *Geotimes, 13*(10), 10–16, 1968*a*.

Wilson, J. T., A reply to V. V. Beloussov, *Geotimes, 13*(10), 20–22, 1968*b*.

Ziegler, A. M., Geosynclinal development of the British Isles during the Silurian Period, *J. Geol., 78,* 445–479, 1970.